Hadronization in cold nuclear matter ⋆

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Abstract

I review a recently proposed scaling analysis of hadron suppression in Deeply Inelastic Scattering on nuclear targets measured at the HERMES experiment. The analysis can distinguish 2 competing explanations for the observed suppression, namely, quark radiative energy loss with long hadron formation times, and prehadron nuclear absorption with hadronization starting inside the nucleus. Experimental data are shown to favor short formation times and prehadron absorption.

Key words: Hadron formation time, radiative energy loss, prehadron absorption.
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One of the most striking experimental discoveries in the heavy-ion program at the Relativistic Heavy Ion Collider (RHIC) has been the suppression of large transverse momentum hadron production in nucleus-nucleus (A+A) collisions compared to proton-proton collisions [1]. An analogous hadron suppression has been observed in Deeply Inelastic Scattering on nuclear targets (nDIS) [2–5], where the observable of interest is the hadron multiplicity ratio

$$R_M^h(z_h) = \frac{1}{N_A^{DIS}} \frac{dN_A^h(z_h)}{dz_h} \bigg/ \frac{1}{N_D^{DIS}} \frac{dN_D^h(z_h)}{dz_h}, \tag{1}$$

i.e., the single hadron multiplicity on a target of mass number A normalized to the multiplicity on a deuteron target as a function of the hadron's fractional energy $z_h = E_h/\nu$, where ν is the virtual photon energy.

On the theoretical side, 2 frameworks are presently competing to explain the observed attenuation of hadron production in nDIS: quark energy loss, with hadron formation outside the nucleus [6–8] and nuclear absorption, with hadronization starting inside the nucleus [9–12]. Distinguishing between these

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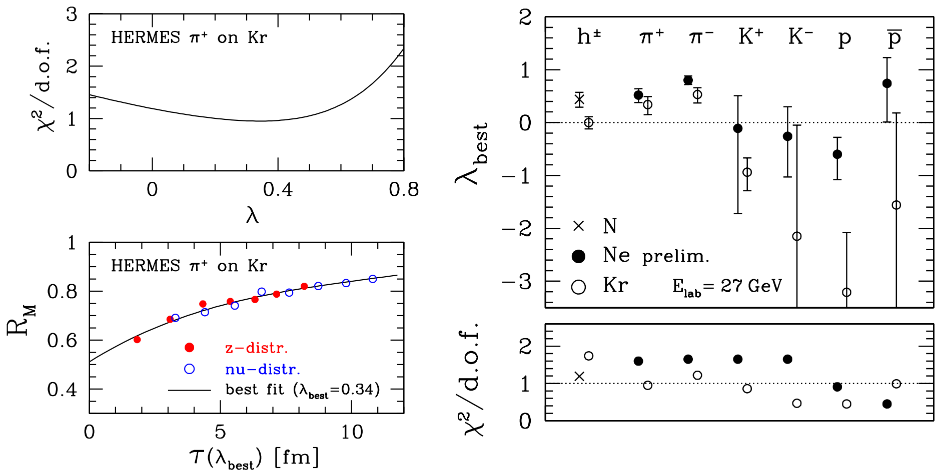

Fig. 1. Left: Extraction of λ and scaling of R_M HERMES data for π^+ on Kr [3]. Right: Scaling exponents with 1σ error bars, and χ^2 per degree of freedom extracted from HERMES data on charged and identified hadrons at $E_{lab} = 27$ GeV [3, 4].

2 different pictures of the space time evolution of hadronization is essential to correctly interpret hadron suppression in A+A collisions as due to parton-medium or hadron-medium interactions, and to correctly extract properties of the produced Quark-Gluon Plasma (QGP) such as its density or temperature from the measured hadron spectra. See Ref. [13] for a review.

In Ref. [14], I proposed a scaling analysis of the experimental multiplicity ratio as a mean of distinguishing quark energy loss from nuclear absorption. Specifically, I conjecture that R_M should depend on z_h and ν only as

$$R_M = R_M[\tau] \quad \text{with} \quad \tau = C\, z_h^\lambda (1 - z_h)\nu \ . \tag{2}$$

The scaling exponent λ is introduced as a way of approximating and summarizing the scaling behavior of experimental data and theoretical models. It can be obtained by a best fit analysis of experimental data or theoretical computations, see Fig. 1. The constant C cannot be determined by the fit. A possible scaling of R_M with Q^2 is not considered in the present analysis. As discussed below, the proposed functional form of τ is flexible enough to encompass both absorption models and energy loss models. The 2 classes of models are distinguished by the value of the scaling exponent: a positive $\lambda \gtrnsim 0$ is characteristic of absorption models, while a negative $\lambda \lesssim 0$ is characteristic of energy loss models. Thus, the exponent λ extracted from experimental data can identify the leading mechanism for hadron suppression in nDIS.

The scaling of R_M is quite natural in the context of absorption models [9–12]. In these models, hadronization is assumed to proceed in 2 steps. First, the struck quark neutralizes its color and becomes a "prehadron", with non-negligible inelastic cross-section with the nuclear medium. Subsequently, and typically outside the nucleus, the prehadron collapses on the observed hadron wave function. The nuclear absorption of the prehadron depends on the in-

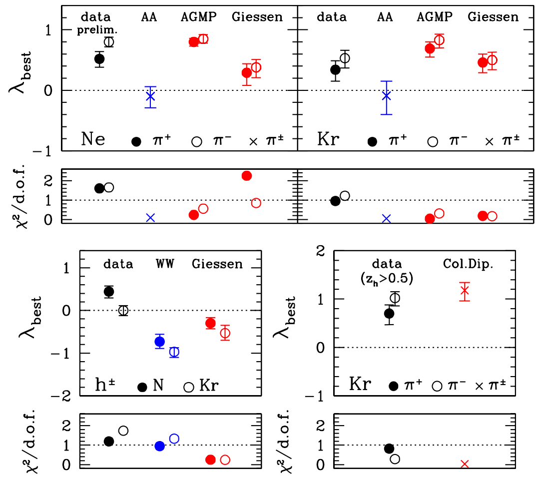

Fig. 2. Comparison of λ from HERMES data [3, 4] and from theory models. Energy loss models (blue points on line): AA [8], WW [6]. Absorption models (red points): AGMP (pure absorption without Q^2-rescaling) [8, 10], Col.Dip. [11], Giessen [12].

medium prehadron path length, which depends solely on the prehadron formation time $\langle t_* \rangle$. In string models [9, 10], as well as in pQCD inspired computations [11],

$$\langle t_* \rangle \propto f(z_h)(1 - z_h) z_h \nu \tag{3}$$

which is well described by the proposed scaling variable τ with $\lambda > 0$. E.g., in the Lund model $\lambda \approx 0.7$. In energy loss models [6–8], the scaling is less obvious. Hadronization is assumed to happen outside the nucleus. Then hadron suppression is due to a reduction of the available quark energy due to medium-induced gluon radiation. The energy ΔE carried away by the radiated gluons is limited by energy conservation to $\Delta E = (1 - z_h)\nu$, which in turn implies an approximate scaling of R_M with $\tau = C(1 - z_h)\nu$, i.e., with $\lambda \approx 0$. In practice it turns out that in energy loss models $\lambda \lesssim 0$. See Ref. [14] for full details. The scaling exponents $\lambda_{\rm best}$ extracted from HERMES data at $E_{lab} = 27$ GeV [3, 4] for different hadron flavors and nuclei are shown in Fig. 1. In all cases χ^2/d.o.f. $\lesssim 1.6$, which proves that R_M scales with τ. The comparison of experimental and theoretical scaling exponents is shown in Fig. 2.

In conclusion, experimental data on pion and charged hadron production have been shown to scale with τ and exhibit $\lambda \gtrsim 0.4$. A discussed, this is a clear indication of the dominance of the prehadron absorption mechanism as opposed to the energy loss mechanism, or in other words it is a signal of in-medium prehadron formation, with formation times $\langle t_* \rangle \lesssim R_A$. The scaling variable τ can then be interpreted as a measure of the formation time of the prehadron, the color neutral precursor of the observed hadron. A more direct detection of in-medium hadronization, and a measurement of the overall scale of the prehadron formation time, is possible by looking at the hadron p_T-broadening, as proposed in Ref. [11]. The outlined scaling analysis will be a useful cross-check

of this measurement. Establishing a scaling of the prehadron formation time with Q^2, as predicted, e.g., in Ref. [11], will further constrain the hadronization mechanism. A dedicated experimental analysis is needed to improve the reach and precision of the proposed scaling analysis. Finally, note that the hadrons observed at HERMES have energies $E_h = z_h \nu \approx 2 - 20$ GeV, which are comparable to mid-rapidity hadrons at RHIC ($E_h \approx p_T$). Thus, at RHIC one may expect hadronization to start inside the QGP.

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